Technology development for the next generation space telescope: an overview

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ABSTRACT

NASA has embarked on the development of the Next Generation Space Telescope (NGST). The NGST is envisioned to be a large aperture (6-10m) deployable infrared telescope with sensitivity 1000 times greater than any currently existing or planned infrared telescope. The scientific goals of NGST include imaging the earliest galaxies and proto-galaxies which formed following the "big bang". Several studies have concluded that the mission is feasible within the proposed cost if a well planned, aggressive technology development effort is implemented early in the development phase. This paper presents an overview of the technology program NASA is pursuing to provide the necessary technology to enable an exciting, affordable NGST mission to launch early in the next century.

Keywords: NGST, telescope technology, large optics, cryogenic optics

1. INTRODUCTION

The Next Generation Space Telescope (NGST) mission[1] is a key element in NASA's Office of Space Science (OSS) strategic planning and is reflected in scientific roadmaps for OSS "Astronomical Search for Origins and Planetary Systems" (Origins) and "Structure and Evolution of the Universe" (SEU) strategic themes. The current NGST vision has its genesis with the report of the "HST and Beyond" blue ribbon committee appointed by the Association of Universities for Research in Astronomy entitled, "*Exploration and the Search for Origins: A Vision for Ultraviolet-Optical-Infrared Space Astronomy*,"[2] which recommended development of a general-purpose, near infrared observatory equipped with a primary mirror larger than 4 meters, cooled to ≤70K, optimized for 1-5 micron observations and placed far from the earth to achieve a sensitivity up to 1000 times greater than any existing or planned facility.

In the summer of 1996, NASA chartered three independent studies which concluded that, with early development of advanced enabling technologies, a large space based infrared telescope with a 6-10m diameter aperture, can provide supreme science return in a timely and cost effective manner. A well planned, adequately funded technology program was recommended progressing from key laboratory innovations, to ground based demonstrations, to selected flight validations and space qualification. Such a program will provide all the necessary elements for an exciting, affordable NGST mission early the next century. Furthermore, the technology developed in support of the NGST mission will enable large space optical systems for future missions such as the Terrestrial Planet Finder and ultimately future planet imagers.

2. TECHNOLOGY PLAN DEVELOPMENT

During the three independent studies conducted in the summer of 1996, teams led by Lockheed-Martin, TRW and the NASA Goddard Space Flight Center (GSFC) evaluated the feasibility of the NGST mission, proposed preliminary architecture concepts and developed technology roadmaps associated with their concepts. The results of these studies were reported at the NGST Study Integration Review held at the GSFC on August 19-23, 1996. Following the formal presentations, participants from the three study teams worked to establish consensus on key technologies to recommend for development based on priority to the NGST mission and maturity of the technology. These recommendations, which are summarized in Table 1 below, are largely the basis for formulating the NGST technology development plan and program. Implementation of the technology plan and program is the responsibility of the NGST Technology and Validation Integrated Product Team (IPT) led by the NGST Project Technologist.

Table 1. Technologies Recommended for Development for NGST

TECHNOLOGY NEED	PRIORITY
Optical Telescope Assembly Technology	
• Ultra-lightweight cryogenic mirrors	1
• Cryogenic actuators	1
• Cryogenic deformable mirror	1
• Deployable structures	2
• Wavefront sensing & optical control	2
Science Instrument Module Technology	
• Low noise, large format near IR & thermal IR detectors	1
• Vibrationless cryo-coolers	2
• Digital micro-mirror array	3
Spacecraft Technology	
• Inflatable or deployable sunshade	1
• Vibration isolation	1
• Low temperature materials property characterization	2
• Advanced startracker	3
Operations Technology	
• Flight software development methodology	1
• Autonomous scheduling and execution	1
• User interaction tools	2
• Autonomous fault management	3
• Control executive	3
• Data compression	3
Systems Technology	
• Integrated modeling tools	1
• System simulator	1

3. REQUIREMENTS

Top level requirements for NGST are based on recommendations made in the "HST and Beyond"[2] committee report. The NGST Study has established mission baseline "Science Floor" requirements along with "Stretch Goals" which are those specifications that would greatly enhance the science return from the NGST mission, but may drive cost. Specific NGST science requirements will continue to be reviewed and assessed by the Science Working Group and will be finalized in the last quarter of FY'99. In the interim, technologies will be developed and evaluated consistent with the scientific "trade-space" shown in Table 2.

Table 2. NGST Scientific Tradespace

Parameter	Science Floor	Stretch Goals
Wavelength Range	1 - 5 microns	0.5 - 30 microns
Angular Resolution	diffraction-limited at 2 µm	diffraction-limited at 0.5 µm
Aperture Diameter	4m	8m
Sensitivity	Zodi-limited at 1 AU	Cosmic infrared background-limited
Lifetime	> 5 years	10 years
Instruments	Wide Field Camera/Spectrometer	Add visible, mid-IR Camera / Spectrometer & Chronograph

The specification of detailed, quantitative requirements for the various developmental technology components, subsystems and systems is the responsibility of the NGST Systems IPT. Preliminary requirements have been established for the major technology items based on analysis of the various mission architecture concepts and an extensive integrated modeling activity ongoing in the Systems IPT. These requirements are captured in the GSFC "Yardstick" or Reference Concept for NGST. As technology products are developed and data is generated in validation testing, the information will be fed back to refine the integrated models and generate more accurate performance predictions and requirements definition.

4. TECHNOLOGY DEVELOPMENT AND VALIDATION PLAN

The NGST Technology and Validation IPT has identified a set of ten key technology products for development and delivery to the mission prior to the implementation phase. These products will be developed, demonstrated and validated to a level of maturity consistent with NASA Technology Readiness Level (TRL) 6 or greater prior to final delivery to the NGST. TRL 6 requires a successful "system/subsystem model or prototype demonstration in a relevant environment (ground or space)". These ten key technology products and an estimate of their current maturity (TRL Level) are shown in Table 3.

Although they do not all explicitly appear in Table 3, all of the Priority 1 & 2 items from Table 1 are being addressed in some form by the NGST Study. Specifically, low temperature materials property characterization is being performed under several of the cryogenic component development tasks. The approach to flight software development methodology is still in the planning phase under the auspices of the Operations Technology element and was the subject of a Flight Software Workshop held as GSFC in September, 1997. Integrated modeling tools and an NGST system simulator are being developed by the NGST Systems IPT.

Table 3. NGST Key Technology Products

Technology Product	Current TRL Level (Est.)
Lightweight Cryogenic Primary Mirror	3-4
Cryogenic Actuators	3-4
Cryogenic Deformable Mirror	2-3
Wavefront Sensing & Control Methodology	4
Precision Deployable Structures	5-6
Vibration Control Methodology	5-6
Large Format, Low Noise IR Detectors	4
Low Vibration. Long Life Cryo-Coolers	4
Lightweight Sunshade	3
Advanced Operations Methodology	4-5

The technology development effort is broken down into five major elements, each with a cognizant leader and a set of defined technology products for which that element is responsible. The primary elements of the plan, the cognizant organization, and areas of responsibility are:

- **Optics Technology**- Responsibility for NGST optics technology development has been delegated by GSFC to the NASA Marshall Space Flight Center (MSFC). The cognizant lead is Mr. Jim Bilbro. MSFC is responsible for development and validation of the lightweight cryogenic primary mirror, the cryogenic deformable mirror, and various types of cryogenic actuators that may be required by NGST. The NASA Langley Research Center (LaRC) is supporting MSFC in development of the cryogenic deformable mirror and actuators.

- **Detector Technology**- Responsibility for the NGST detector technology development has been delegated by GSFC to the NASA Ames Research Center (ARC). The cognizant lead is Dr. Craig McCreight. ARC is responsible for the development and validation of the large format, low noise near IR and thermal IR detectors for NGST including both the sensing arrays and the readout electronics.

- **Spacecraft Technology**- Responsibility for development and validation of a number of spacecraft related technologies resides in this element including precision deployable structures, vibration control, a lightweight sunshade and low vibration cryo-coolers. The technology providers include several NASA centers and industry partners and consequently, no specific center has responsibility for this entire area. The current cognizant lead for this element is Dr. Dan Coulter, of the Jet Propulsion Laboratory (JPL), the NGST Project Technologist and Technology & Validation IPT lead.

- **Developmental Cryogenic Active Telescope Testbed (DCATT)-** Responsibility for implementation of the DCATT testbed has been assigned to the GSFC. The cognizant lead is Ms. Claudia LeBoeuf. GSFC, with support from JPL and MSFC, will develop and demonstrate in subscale hardware, the system level methodology for alignment, phasing and wavefront sensing & control of a segmented space telescope.

- **Operations Technology-** Responsibility for the NGST operations technology development and validation has been assigned to the GSFC. Mr. Keith Kalinowski is the cognizant lead. GSFC will develop and validate advanced and autonomous operations methodology for both the flight and ground portions of NGST operations. Specific capabilities under development include an Autonomous Scheduler and a Scientist's Expert Assistant for aid in proposal writing and observation planning.

In addition to the five major technology development elements, there are two other important functional elements of the Technology and Validation IPT. The first of these is the Industry Directed Technology element under which the two pre-phase A architecture study contractors (Ball Aerospace and TRW) perform technology development as outlined in their technology roadmaps. These effort are funded by and with the concurrence of the NGST Study. The NGST Study Technologist is responsible for this element. Second, is the Pathfinder Validation Flight element which is a GSFC led activity under the cognizance of the Technology and Validation IPT Deputy Lead. This element is responsible for planning and implementing a series of cost effective flight experiments intended to validate key elements of NGST technology in the space environment.

5. TECHNOLOGY PRODUCT DEVELOPMENT APPROACH

A brief description of the approach for development and validation of each of the ten technology products listed in Table 3 follows.

- **Lightweight Cryogenic Primary Mirror-** Technology for the primary mirror will be developed primarily under the NGST Mirror System Demonstrator (NMSD) RFO, a competitive procurement from the MSFC for 2m class mirrors meeting the NGST requirements for mass, figure and cryogenic performance. The 2m size is similar to what might be expected for a segment of a 6-8m diameter mirror. The products will include the mirror itself, the mirror support structure, and all necessary actuators and drive electronics. Two NMSD awards have been made to teams led by the University of Arizona and Composite Optics. Both of the proposed concepts utilize thin glass reflectors and lightweight composite support structures. The NMSD mirrors will be interferometrically tested at temperatures down to ≤77K either at contractors facilities or at the MSFC. Plans are in progress to modify the AXAF test facility to accommodate such an optical test with the mirrors in a vertical orientation in order to simplify the interpretation of the effect of gravity without a complex off-loading scheme. The mirrors will also be dynamically tested to the levels and spectrum appropriate for an Atlas 2 launch and orbit insertion. In addition to the NMSD activities, several smaller efforts, including work by the architecture study contractors under their Industry Directed Technology Development, are in progress and one or more competitive procurements are planned focusing, in particular, on advanced mirror materials including SiC, Be and Ni. In the event that one or more of these or other non-traditional materials shows substantial promise in a timely manner, an Advanced Mirror System Demonstrator (AMSD) RFO is planned to further the technology to a level meeting the NGST requirements. Finally, several efforts to produce cryogenic mirrors are in progress under the Large Aperture Space Telescope Topic of the NASA SBIR program. MSFC is the lead center for this topic and will monitor progress and incorporate the results into the overall mirror development plan.

- **Cryogenic Actuators-** Cryogenic actuator technology will be developed primarily under the NGST Cryogenic Actuator RFO, a competitive procurement from the LaRC for three different classes of actuators meeting the NGST requirements for stroke, resolution, power, mass, and cryogenic performance. Proposals have been solicited and received for position actuators, force actuators and actuator arrays suitable for developing cryogenic deformable mirrors. As of this writing, the proposals are under review and multiple awards are anticipated soon. The products will include design studies in phase 1 and in phase 2, prototype actuators and drive electronics will be produced. Performance will be validated in the cryogenic actuator test facility at JPL or similar facilities at LaRC or GSFC. In addition, several NASA SBIR efforts are in progress to produce cryogenic actuators. These efforts will be monitored and the results integrated into the overall NGST cryogenic actuator development strategy. Finally, efforts are planned in this area by the architecture study contractors under their Industry Directed Technology Development.

- **Cryogenic Deformable Mirror-** Cryogenic deformable mirror technology will be developed under a combination of the NGST Cryogenic Actuator RFO, the NASA SBIR program and the NGST Cryogenic Deformable Mirror RFO from the MSFC. The NGST Cryogenic Actuator RFO is a competitive procurement from LaRC which includes development of a small (10 x 10) actuator array meeting the NGST cryogenic deformable mirror requirements for stroke, resolution, power, mass, and cryogenic performance. As of this writing, it is anticipated that one or more awards will be made for development of this class of actuator product. In addition, Xinetics, Inc. has recently completed a Phase 1 SBIR effort under the Large Aperture Space Telescope Topic to show feasibility of producing a cryogenic deformable mirror meeting NGST requirements. A Phase 2 award, recently announced, will allow continuation of this effort leading to a functional prototype actuator array. Following the completion of the SBIR efforts and the Cryogenic Actuator RFO effort, a Cryogenic Deformable Mirror RFO is planned from MSFC to build a fully functional prototype mirror including necessary drive electronics and software.

- **Wavefront Sensing & Control Methodology-** Technology for alignment, phasing and wavefront sensing and control will be developed primarily under the auspices of the NGST Systems IPT and the Developmental Cryogenic Active Telescope Testbed (DCATT) activity centered at GSFC. A concept for a layered control approach utilizing image based sensing, as well as the software to implement it, is under development by the Systems IPT. DCATT will implement the approach in subscale hardware by development of an actively controlled 1m class telescope with a segmented primary. The primary segments will be actuated and controlled in 6 DOF and the secondary will also be controlled in 6 DOF. An active optics bench will include relay optics, a deformable mirror, a fast steering mirror and a coarse and fine wavefront sensor. A stimulus and scoring interferometer will complete the testbed. Operation is planned in three phases. Phase 1 will include room temperature operation with mostly off the shelf components to investigate and validate the fundamental optical control scheme. In Phase 2, the telescope (with its mostly off the shelf components) will be re-located to a cryogenic chamber during operation. The active optics bench will remain outside at ambient temperature. The principal goal of this phase is to evaluate performance of the cold telescope relative to the predictions of the NGST Integrated Models built by the Systems IPT. Finally, in Phase 3, the telescope will be retro-fitted with flight-like components and cryogenically tested to validate performance and modeling of the flight-like components. The active optics bench will remain at ambient temperature. (Components on the active optics bench will be separately tested at cryogenic temperature to validate critical performance.) These efforts will investigate and evaluate techniques for coarse and fine wavefront sensing, coarse alignment of the primary mirror segments and the secondary mirror, phasing of the primary mirror segments, wavefront correction with the deformable mirror, and image stabilization with the fast steering mirror as well as thermal effects on the telescope. Results will be compared to predictions from the NGST integrated modeling activity under the Systems IPT and the models will be upgraded and validated. Future efforts may include evaluation of alternative schemes for wavefront sensing and control. In addition to the GSFC led effort, the architecture study contractors are addressing various aspects of optical control technology as part of their Industry Directed Technology Development.

- **Precision Deployable Structures-** The technology for precision deployment is fairly mature in light of the requirements generated by the Systems IPT integrated modeling team. Considerable expertise in this area resides in the US aerospace industry. Thus, the principal source for technology to deploy the primary mirror, the secondary mirror and possibly other large structural elements of NGST is the architecture study contractors Industry Directed Technology Development and internal IRAD efforts. Several testbeds will be constructed to evaluate different schemes for precision deployment. Stability, including microstability of large deployed structures will be evaluated in relevant environments. The results will be compared to the anticipated dynamic range of the NGST optical control system and will be used to upgrade and validate the integrated models.

- **Vibration Control Methodology-** It is anticipated that the technology to stop vibrations arising from, for example, the spacecraft reaction wheels from reaching the Optical Telescope Assembly (OTA), through a combination of passive and active isolation and control will be available on the time scale that NGST enters its implementation phase (C/D/E). Consequently, current plans call for minimum efforts in this area. Other NASA missions, including the Space Interferometry Mission are developing techniques in this area that will meet the NGST needs at frequencies >1Hz. The USAF Phillips Research Site as well as several large aerospace contractors are also developing passively and actively controlled structures and structural members. Very low frequency vibrations which may be associated with the large sunshade will be eliminated with the fine guidance control system. Both the DCATT testbed and the architecture study contractors will evaluate the efficacy of this technique. All of these efforts will be monitored along with the progress in the development of quiet reaction wheels and the results will be integrated into the vibration control methodology development strategy.

- **Large Format, Low Noise IR Detectors-** The technology for the IR detectors for NGST will come from a combination of efforts currently ongoing under the NASA Origins NRA and an NGST Detector RFO from ARC. Current efforts include: (1) the development of up to 1k x 1k low noise InSb arrays at the University of Rochester in collaboration with SBRC; (2) the development of up to 512 x 512 Si:As IBC arrays at Cornell University with SBRC; and (3) the development of up to 512 x 512 low dark current HgCdTe arrays at the University of Rochester with Rockwell. In addition to these efforts, a competitive NGST Detector RFO is planned to address alternative sensor development, readout electronics and to demonstrate 2-D mosaicing of the arrays and the readouts. Low noise cryogenic readout electronics and a Focal Plane Array Testbed are being developed under the Industry Directed Technology Development portion of the architecture studies. Ultimately, an NGST Science Instrument Testbed will be developed and prototype science arrays and readouts will be evaluated and validated as part of this effort.

- **Low Vibration, Long Life Cryo-Coolers-** A substantial effort in the development of quiet coolers for astronomical applications is on-going under the NASA Crosscutting Technology Program managed and funded out the Code SM. NGST, consequently, does not plan to pursue a major effort in this area. Two coolers are currently under development in the Crosscutting Program which will meet the needs of NGST. The baseline NGST cooler is a miniature version of Turbo-Brayton Cooler which is being developed out of GSFC at Creare, Inc. A moderate size version of this cooler has been developed and will be demonstrated on a Shuttle flight in the near future. The design and fabrication of a smaller version for NGST is in progress at Creare. As a backup, NGST has the sorption cooler technology currently being developed for the Far Infrared and Submillmeter Space Telescope (FIRST) mission at JPL. NGST plans modest co-investments in these two development activities in order to take the development to a prototype demonstration stage.

- **Lightweight Sunshade-** A large, lightweight sunshade is necessary to shield the NGST from the solar radiation and allow it to passively cool to its operational temperature. Several designs have emerged utilizing multiple membranes which operate much like multi-layer insulation and which can be stowed efficiently for launch. A reliable deployment mechanism is required. Schemes much like those that enable large antennas such as TDRSS to be deployed are possible for the NGST sunshade, however, the current baseline is an inflation deployed shade. The technology for the inflation methodology and the inflatable structure will be developed as part of the Inflatable Technology Program at JPL funded by NASA Code SM. A competitive procurement for the technology development culminating in a subscale ground demonstration is planned. The inflation methodology, rigidized struts and the ≈1/5 scale ground test model will be developed. GSFC, in collaboration with LaRC, will develop and/or select the thermal membrane materials. The first NGST pathfinder flight validation experiment is planned to carry a 1/2 scale inflation deployed sunshade. The flight experiment is expected to provide information on deployment, dynamics, and thermal performance of such a shade in space. The data will be utilized validate and upgrade thermal and structural models of the sunshade which will become elements of the NGST Integrated Models.

- **Advanced Operations Methodology-** The NGST operations technology development will be largely performed by the Operability IPT at GSFC. The principal products are planned to be an adaptive scheduler, a scientist's expert assistant and an NGST Operations Testbed. Currently, the adaptive scheduler is under development. This is an object oriented code that will eliminate the need to time tag each event in a sequence and will enable autonomous execution of tasks by the spacecraft. The scientist's expert assistant is also under development as a tool which will reduce the need for potential PI's to access "contact scientists". It will facilitate proposal writing and observational sequence planning. This tool is planned to be beta-tested with the Hubble Advanced Camera after the 2000 servicing mission to HST. Future efforts include development of advanced flight software methodology based on missions such as Mars Pathfinder and ultimately, development of an Operations Testbed module for the System IPT's NGST Simulator.

6. NGST FLIGHT SYSTEM TESTBED

The NGST Flight System Testbed is planned to be a nearly full scale, fully functional, "flight like" model of the NGST. It will be built at the system contractors facility after the down-selection to a single contractor and single architecture at the end of Phase A. It will likely be an outgrowth of one or more testbeds built during earlier technology development activities, however, it will utilize the architecture and technologies that have been selected for the flight build and will validate many aspects of the system level performance. Detailed plans for the development and utilization of this testbed will be requested as part of the Phase B proposals. It is anticipated that successful development and operation of this testbed during phase B will be a key element in proving readiness to move to the implementation phase of NGST. It is also expected to be useful during the flight build, integration and test phase and serve much of the role traditionally served by an "engineering model".

7. ISIS FLIGHT EXPERIMENT

The first Pathfinder flight experiment, called ISIS, is planned to be a low-cost flight demonstration and validation of an inflation deployed sunshade for NGST. Current plans call for an approximately half scale version of the shade to be flown on a shuttle deployed, free-flying spacecraft such as the German ASTROSPAS or the GSFC Spartan. The duration of the flight would be expected to span one shuttle mission. The goals of the experiment are to test out suitable membrane materials, demonstrate a controlled inflation sequence, demonstrate rigidization of the support structure, measure flight dynamics, measure thermal performance and compare results to predictions of the NGST system models. Many elements of the shade performance simply cannot be practically tested on the ground and this flight is required to understand the risk of using this new technology for a large sunshade for NGST.

Considerable additional space, mass, power and data storage, beyond that required for the inflatable shade experiment, is likely to be available on the ISIS flight to support multiple small experiments. A series of low-cost attached payloads such as Hitchhikers or GAS Cans is also planned for ISIS. The intent is to provide technology developers with access to the space environment to gain information on key performance characteristics of their component level technologies in space. Examples of this type of experiment could include measuring the effects of gravity off-loading on thin membrane mirrors, measuring the effects of zero-g on precision joints and latches, evaluating the stability of deployable booms, etc.

8. NEXUS FLIGHT EXPERIMENT

The final Pathfinder flight experiment, termed NEXUS, is planned to demonstrate deployable optics in the space environment. This is perhaps the most important technology demonstration to validate a deployable telescope as a practical approach to large space telescopes and reduce the risk for using large deployable optics for space telescopes. The system contractors will be required to describe, in detail, their approach to partnering with NASA to implement this flight experiment in their Phase A and Phase B proposals. The goal is to build, launch and operate a segmented, deployable ≥2m diameter aperture telescope and demonstrate diffraction limited imaging of a bright star or other celestial object. The flight will be on a long duration version of the ASTROSPAS or Spartan spacecraft and will span at least two shuttle flights (several months). The telescope itself will mimic the NGST architecture and will be provided by the system contractor. The flight will be near the end of the formulation phase of NGST and along with the Flight System Testbed and other accomplishments, will provide evidence that the NGST team is ready to proceed to the implementation phase.

9. SUMMARY

Early development of advanced technologies from ultra-lightweight mirrors to autonomous ground and flight operations will enable the Next Generation Space Telescope to provide astronomers with maximum science return in a timely and cost effective manner. We have concluded, based on the findings of the three independent study teams, that no new inventions or science is required to accomplish the NGST mission. A well planned, adequately funded technology program as described in this paper, including a steady progression from key laboratory innovations, to ground based demonstrations, to selected flight validations and space qualification will provide all the necessary elements for an exciting, affordable NGST mission early in the next century.

10. ACKNOWLEDGMENT

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11. REFERENCES

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